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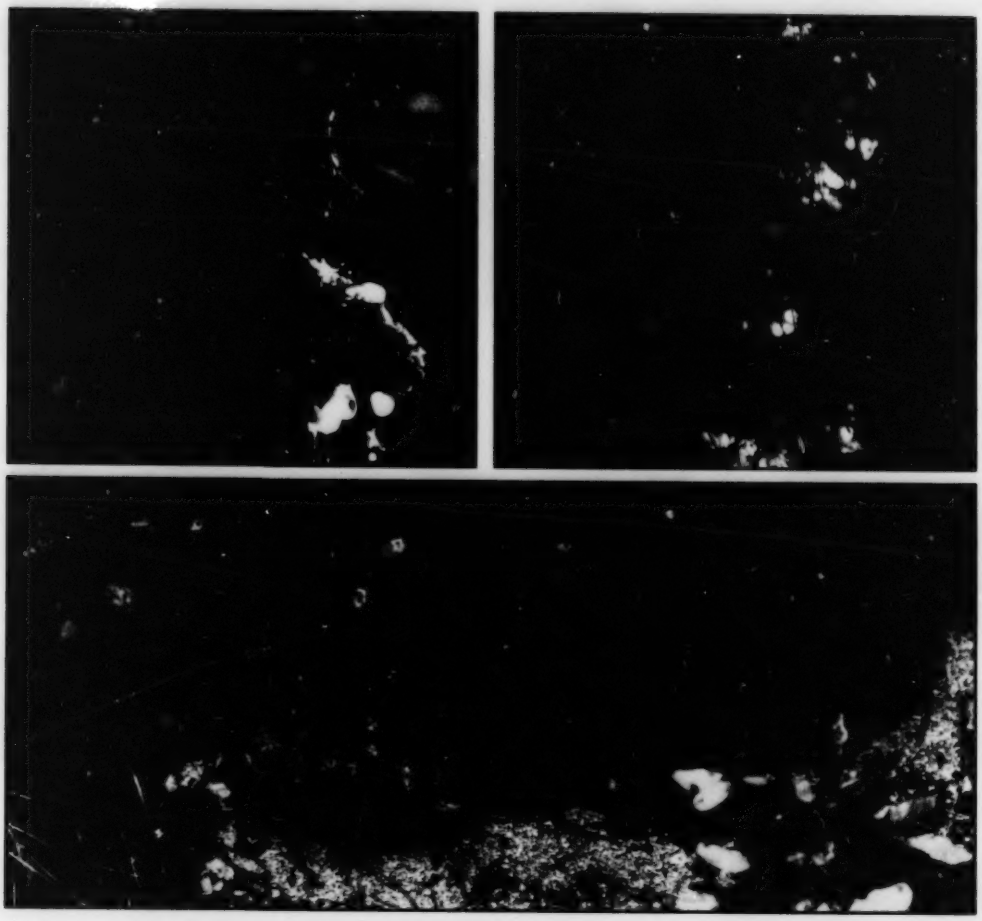

Les Safranyik and Douglas A. Linton

Information Report BC-X-392

Natural Resources Canada
Canadian Forest Service
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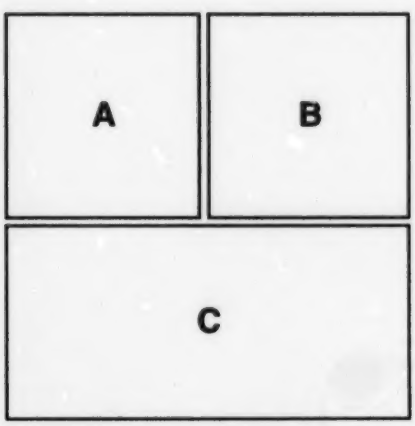

Cover photos:

A. Pitch tube on the bole indicating current attack by mountain pine beetle.
B. Bark was stripped from the bole of this infested tree by woodpeckers searching for mountain pine beetle brood.
C. Boring dust at the base of a freshly infested tree.

Abstract

Regression equations describing the probability of detecting lodgepole pines infested by the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) at different distances from a line were derived from thirty-six 50-m line transects. Each transect line was traversed independently by two cruisers at a normal walking pace, and all infested trees were counted. The distance of each tree from the line was then measured, and assigned to 2-m-wide strips parallel to the line to a maximum width of 20 m. Fixed plots centered on each line were established, enclosing all of the trees previously identified. All of the trees within the fixed plots were examined for attack in order to determine the rates of error and the precision of the line intersect cruises. Three prism plots were placed along each transect line to provide further comparisons and stand parameters. Based on the data, a histogram of the probability of detecting a currently infested tree over distance from the transect line (the detection curve) was constructed. Both a simple linear regression and a logistic regression gave a good fit to the data. Based on a linear relationship between the probability of detecting an infested tree and perpendicular distance from the transect line, the estimated density per ha ($\hat{A}$) of currently infested trees had the following form: $\hat{A} = 10{,}000nb/La^2$, where n = number of currently infested trees seen, b and a are the slope and intercept of the detection curve, L = transect length (m). The estimate from this equation agreed closely with the corresponding estimates from prism plots and fixed plots and there were no significant differences among the corresponding overall densities. Both cruisers mistakenly tallied some trees from the transects that were not currently infested (commission error). The probability of commission errors was independent of infested tree density and distance from the transects. The method used in constructing the detection curve reduced the possible bias in the estimated density due to this problem. In practice, it is recommended that each person develop his or her own detection curve and equation for estimating the density of currently infested trees.

Résumé

Des équations de régression décrivant la probabilité de détection de pins tordus latifoliés infestés par le dendroctone du pin ponderosa (*Dendroctonus ponderosae* Hopkins) à différentes distances d'une ligne ont été dérivées de trente-six transects de 50 m. Deux personnes, à un pas de marche normal, ont traversé chaque transect de façon indépendante et ont dénombré les arbres infestés. La distance séparant chaque arbre de la ligne a ensuite été mesurée et assignée à des bandes de 2 m de largeur parallèles à la ligne jusqu'à une largeur maximale de 20 m. Des placettes fixes centrées sur chaque ligne et entourant tous les arbres précédemment relevés ont été établies. On a examiné tous les arbres à l'intérieur de ces placettes afin de vérifier s'ils étaient attaqués et ainsi de déterminer les taux d'erreur et la précision des inventaires par échantillonnage linéaire. Trois placettes circulaires à rayon variable, établies par la suite le long de chaque transect, ont servi à faire d'autres comparaisons et ont fourni des paramètres de peuplement additionnels. Les données recueillies ont servi à bâtir un histogramme de la probabilité de détection d'un arbre actuellement infesté en regard de la distance avec le transect (la courbe de détection). À la fois une régression linéaire simple et une régression logistique décrivaient bien les données. D'après la relation linéaire entre la probabilité de détection d'un arbre infesté et la distance perpendiculaire au transect, la densité estimée par ha ($\hat{A}$) d'arbres actuellement infestés avait la forme suivante : $\hat{A} = 10\,000\ nb/La^2$, où n est le nombre d'arbres actuellement infestés relevés, b et a sont la pente et le point d'intersection de la courbe de détection, et L est la longueur du transect (m). L'estimation obtenue au moyen de cette équation concordait étroitement avec les estimations correspondantes établies à partir des placettes circulaires à rayon variable et des placettes fixes, et il n'y avait pas d'écarts significatifs entre les densités globales correspondantes. Les deux personnes ont par erreur dénombré des arbres des transects qui n'étaient pas actuellement infestés (erreur commise). La probabilité d'erreurs commises était indépendante de la densité d'arbres infestés et de la distance par rapport aux transects. La méthode utilisée pour construire la courbe de densité réduisait, dans l'estimation de la densité, le biais possible attribuable à de telles erreurs. En pratique, il est recommandé que chaque personne élabore sa propre équation et courbe de détection pour évaluer la densité des arbres actuellement infestés.

Introduction

The mountain pine beetle, *Dendroctonus ponderosae* Hopk., is the most damaging bark beetle of mature lodgepole pine, *Pinus contorta* Dougl., forests of western North America. These beetles attack trees in large numbers and infested trees usually begin dying with a few weeks after attack from the combined action of associated fungi carried into the tree by the beetles and girdling of the living bark and phloem.

The usual external symptoms of trees currently infested by mountain pine beetle are pitch tubes on the bole, boring dust in crevices in the bark on the lower bole and on the ground, or flaking of the bark by woodpeckers searching for mountain pine beetle brood (see illustrations on cover). Infested trees normally have green crowns or at least part of the crown faded to yellowish-green to bright red, depending on the season of observation (Safranyik *et al.* 1974). Thus, in addition to the observer experience, the reliability of detection is expected to be a function of sighting distance and may also be affected by some stand and site characteristics.

During ground probes to detect trees currently infested by mountain pine beetle, it is desirable to obtain estimates of the density of infested trees in specific areas. This could be achieved by conventional quadrant sampling or plotless sampling methods, such as prism cruising. These methods however, tend to be time-consuming due to the need to delineate plots and count affected trees, or to measure tree diameters as required for estimating density using prism cruise data. Moreover, sample surveys using these conventional methods would be difficult to implement by single persons normally involved in doing the ground probes. On the other hand, line transect sampling could potentially be done by one person using only a hip chain and compass.

Line transect sampling has been used for at least 7 decades for estimating wildlife abundance (Burnham *et al.* 1980; Seber 1982; Buckland *et al.* 1993). It is a potentially useful method for estimating the abundance of a wide range of objects, including the density of immobile objects such as killed or diseased trees in the forest. The use of the method requires that at least one line be established in the area to be sampled. The line is traversed with the objective of detecting a sample of the target objects, as not all potentially detectable objects will be found; objects near the transect line are more likely be detected than objects farther away.

The basic principles of line transect sampling (Burnham *et al.* 1980) are:

1 The objects to be sampled in an area are distributed in accordance with a stochastic process with a certain density per unit area.

2 A line of known length is randomly located and traversed. Objects detected on either side of the line are recorded including either: a) perpendicular distance or b) sighting distance and angle for each detected object.

Usually several randomly placed lines are used. Hence, as long as the transect lines are randomly located it is not necessary to assume that the objects are randomly or even independently distributed.

There are four assumptions:

- Objects located directly on the line will always be detected;
- Points are not counted more than once;
- Distances and angles are measured without error;
- Detection of objects are independent events.

The objective of this research was to assess the potential of the line transect method for estimating the density of lodgepole pine recently infested by mountain pine beetle. The study was restricted to using measurement of perpendicular distances from the transect lines to sighted trees in order to estimate the density of infested trees.

Methods

In line transect surveys, the general estimator of density per unit area ($\hat{A}$) is given by equation (1).

$$\hat{A} = n/2L\hat{u} \qquad (1)$$

Where n = number of objects sighted, L = length of the line transect, and $\hat{u}$ = is an estimate of one half of the effective strip width about the line transect (Burnham *et al.* 1980). $\hat{u}$ is closely related to the average probability of detection over the searched area

Thus the problem of estimating the density of objects is essentially that of estimating one unknown parameter, $\hat{u}$. As this parameter is related to the so-called detection function, i.e., the probability of observing a randomly selected object given a perpendicular distance x, the approach taken in this study was to determine the detection function from field data.

To determine the detection function, the relationship between the average probability of detecting an infested tree and the perpendicular distance to a line transect, and some factors affecting this relationship was examined based on field surveys.

Field procedures

Line transect surveys were carried out in lodgepole pine stands infested by mountain pine beetle near Princeton and Manning Park in southern British Columbia during late summer in 1999 and again in 2000. Thirty-six 50-m line transects were established and cruised at four locations. At each location, the line transects were placed end-to-end with 25-m gaps between them. To establish a transect line, a 50-m tape was pulled taut and laid on the ground. Both members of the two-person crew tallied attacked trees on each side of the line marked by the tape. The tally was performed by proceeding along the length of the tape at a walking pace, each person examining the trees and recording data on one side of the line only. If a suspected infested tree was seen, the distance from the point of origin of the line was recorded. When the end of the tape was reached, the crew returned to the start point, changed sides, and each then tallied the other side, so both sides were examined by the two cruisers. Every effort was made to ensure that the sampling was done independently and without pauses to examine individual trees in detail.

After both sides of a line were tallied, the perpendicular distance from the line to each sighted tree was measured and recorded. The infestation status of each suspect tree was assessed and recorded as either confirmed infested or not infested. The maximum distance of an attacked tree from the line was determined. That distance plus 2 m was used as the half-width of a fixed plot centered along the length of the line transect. All trees within the fixed plots were closely examined and the attack status of each tree was determined. All attacked trees not sighted from the line during the walk-through survey were tallied in a similar fashion to those seen from the line. Trees found from the line were identified as such in the fixed plot tally, and all attacked or suspected attacked trees were classified as having been spotted from the line by one, two, or none of the cruisers, or as incorrectly tallied.

Prism sweeps were done using a BAF 5 m prism with centers at 15, 30 and 50 m on each transect line. Dbh (tree diameter at 1.3 m) of all trees in the prism plots was recorded.

Analysis

Numbers of attacked and non-attacked trees per hectare were calculated for each line transect from prism plot data and fixed-plot data. The data from all transects were combined and sorted to provide total trees per 2-m-wide strip to a maximum distance of 20 m from the line. The average proportion (± S.E.) of confirmed infested trees per strip was calculated for each cruiser and for all data combined. Errors of omission (infested trees not seen) and commission (trees wrongly identified as being infested) were compiled in the same manner.

Correlation analysis was used to examine the effects of tree and stand characteristics on the average probability of detecting infested trees and the occurrence of errors of commission and omission. Average proportions per line transect of infested trees missed and trees wrongly identified as being infested were compared between cruisers by

paired t-test. The histogram for the average probability of detection on perpendicular distances to the transect lines was described separately for each cruiser and for the combined data by linear regression and a logistic regression. The significance level of the correlation coefficient combined with visual inspection of the plotted residuals was used to determine the best fit. The best linear regressions were compared between cruisers for differences in slope and intercept by ANOVA. The value of $\hat{u}$ was estimated by integrating the detection curve from zero to a perpendicular distance equal to the x-intercept, for linear regressions, or integrating from zero to infinity for the logistic regression. Infested tree density was estimated for each line transect based on the best fitted regression. Mean density was compared with corresponding means estimated from the fixed plots and prism plots by paired-t tests.

Results

Tree and stand statistics for the line transect cruise data are given in Table 1. Just over 50% of the currently infested lodgepole pines located within an average maximum distance of 6.44 m on either side of the transect lines were seen by both cruisers. On average, the transects traversed dense patches of currently infested lodgepole pine as indicated by the high average density of currently attacked trees (Table 1).

Table 1. Tree and stand parameters for the 50-m transect lines cruised by each of two persons in lodgepole pine stands infested by the mountain pine beetle.

Variable	Sample size (N)	Mean	Standard Deviation
Confirmed proportion of infested trees seen by #1	34	0.5355	0.2757
Confirmed proportion of infested trees seen by #2	34	0.5263	0.2690
Proportion misidentified by #1	34	0.0735	0.1535
Proportion misidentified by #2	34	0.2224	0.4585
Max. distance from transect line (m)	34	6.4375	5.0273
Total basal area (m^2/ha) per hectare	35	39.2381	12.0923
Avg. tree diameter at 1.3 m (dbh) (cm)	35	29.0074	8.0143
Previously killed trees per ha	17	128.4679	120.6837
Currently infested trees per ha	35	102.5862	133.6706

Table 2. Pearson correlation coefficients between tree and stand variables, the proportion of infested lodgepole pines trees and proportion of trees misidentified as being infested by each of two cruisers on thirty-four 50-m-long transects. Due to missing data, sample size varied from 17 to 35. Correlation coefficients printed in bold are significant at probability levels of at least 0.05.

Proportion of trees correctly identified		Proportion of trees misidentified		Max.		Basal area per ha		Infested trees per ha	
by #1	by #2	by #1	by #2	observed distance	Avg. DBH	Total	Old killed trees	New	Old
1.000	**0.356**	0.100	**0.348**	-0.001	-0.079	**-0.472**	-0.197	0.007	0.126
	1.000	0.174	0.251	0.046	-0.045	-0.100	-0.037	0.199	0.223
		1.000	**0.415**	**0.352**	**-0.486**	0.155	**-0.452**	**0.446**	**-0.441**
			1.000	0.142	-0.160	-0.122	-0.329	0.227	-0.263
				1.000	-0.314	0.165	-0.343	0.215	-0.011
					1.000	-0.216	0.349	**-0.605**	-0.347
						1.000	0.4093	0.318	0.410
							1.000	0.084	**0.681**
								1.000	**0.579**
									1.000

The proportion of confirmed infested lodgepole pines and the proportion of trees misidentified as being infested were significantly and positively correlated between the two cruisers (Table 2). The maximum distance at which confirmed infested trees were sighted was not correlated with the proportion of confirmed infested trees detected from the transect lines. For cruiser 1, the proportion of confirmed infested trees was positively correlated with the proportion of misidentified "infested" trees by cruiser 2, and negatively correlated with total basal area per ha. For cruiser 2, the sign of the corresponding correlation coefficients was the same, but the correlation was not significant. For cruiser 1, the proportion of misidentified "infested" trees was positively related to both the density of currently attacked trees and the maximum distance of sighting infested trees, and negatively related to average stand diameter as well as to the basal area and density of previously killed trees (Table 2). For cruiser 2, the signs of the corresponding correlation coefficients were the same but the correlations were not significant.

For the combined data from both cruisers the misclassified trees, expressed as proportions of the total number of confirmed infested trees within each 2-m strip, were not correlated with the distance from the transect lines ($r = 0.366$, df =7, $p = 0.377$). So, distance did not have a significant effect on the accuracy of identifying currently attacked trees. Similarly, the correlation between the number of confirmed infested trees by distance and the number of misclassified trees was not significant ($r = 0.506$, df = 7, $p = 0.104$).

Average stand dbh was negatively correlated with the density of currently attacked trees (Table 2) indicating that, in the pure lodgepole pine stands cruised, the trees with larger dbh were killed by earlier attack. In mixed stands the non-host trees, Douglas-fir and spruce, were generally larger than lodgepole pine. The basal area and density of previously killed lodgepole pine were positively and significantly correlated (Table 2) because each year the beetle tends to kill the largest diameter component of stands. The significant positive correlation between the density of previously killed and currently infested lodgepole pine is an indication that mountain pine beetle infestations tend to persist for a number of years in the same area.

The linear regression equations for the proportions of confirmed infested trees seen (Y) vs. the mid-point distance from the transect lines (X) of 2-m wide strips were as follows:

Cruiser 1: $Y_1 = 0.6899 - 0.0364X,\ n = 9,\ r = 0.907$ (2)

Cruiser 2: $Y_2 = 0.7794 - 0.0357X,\ n = 9,\ r = 0.851$ (3)

There were no significant differences in the coefficients of the two regressions (Wilk's lambda = 0.9987; F, 1df = 0.0087, p> 0.92). Therefore, the data were combined and a new regression, the detection function, was calculated.

Combined data: $Y_c = 0.9014 - 0.0356X,\ n = 9,\ r = 0.884,\ p = 0.002$ (4)

The regression, for dat, summarized by 2-m distance intervals, is given in Figure 1. The intercept was not significantly different from 1 ($t = 1.516$, df =1, $p = 0.173$). The shape of the histogram based on the confirmed numbers of infested trees sighted by one or both cruisers (Figure 2) was different from Figure 1 and resembled a negative exponential function. The regression of the probability of sighting currently infested trees, averaged for the two cruisers, on class-midpoint distance (5) had similar coefficients to (4).The intercept was not significantly different from 1 ($t = 1.607$, df =1, $p = 0.152$).

Averaged data: $Y_m = 0.8827 - 0.0397X,\ n = 9,\ r = 0.911,\ p = 0.001$ (5)

In addition to the simple linear curve, a logistic function of the form $ln\ (Y/(1-Y)) = A + B\ X$ was fitted to the data, where Y = probability of detecting an infested tree at sighting distance X and A and B are regression parameters. A and B were estimated by maximum likelihood. This model also gave a good fit to the data. For example, for the combined data the fitted model (6) gave nearly identical predictions of detection probabilities as those given by equation (4).

$$Y = [\exp(1.997 - 0.176X)] / [1 + \exp(1.997 - 0.176X] \quad (6)$$

(2 x log likelihood = 18.683 with 1df Chi-square p-value < 0.0001)

The coefficients of detection functions (4) to (6) can be used to estimate $\hat{u}$ in (1). Designating the intercept and regression coefficient in (4) and (5) by the letters a and b, respectively, an estimate of $\hat{u}$ is calculated as the integral from 0 to the point where the regression line intercepts the x-axis ($X = a/b$). Hence, $\hat{u} = (a^2/b) - (b/2)(a/b)^2 = a^2/2b$. The corresponding estimate from (6) is $\hat{u} = \{ln[abs((1+expA)/B))]\}$, where ln = natural logarithm, abs = absolute value, and the other symbols are as defined earlier.

Based on (1), the estimate of the density of currently infested trees from (4) or (5) is as given in (7).

$$\hat{A} = 10{,}000nb/La^2 \qquad (7)$$

Where L = length of the line transect (m), n = number of sighted currently infested trees, including commission error, and the other symbols are as defined earlier.

The corresponding estimate based on (6) is given in (8)

$$\hat{A} = 10{,}000n/2L\{ln[abs((1+expA)/B))]\} \qquad (8)$$

Note: Density estimates based on (7) and (8) assume that infested trees were counted on both sides of the transect lines. It is permissible to make counts on just one side of the transects. In this case, the right hand sides of (7) and (8) need to be multiplied by 2.

The linear regressions of the estimated number of currently infested trees per ha (Q) based on equation (4) and the number of attacked trees per ha from a prism cruise (P) and a fixed plot cruise (Z), and the regression of P vs. Z, were as in (9), (10), and (11), respectively.

$$Q = 41.839 + 0.3803P,\ n = 34,\ r = 0.663,\ p < 0.001 \qquad (9)$$

$$Q = 12.441 + 0.8492Z,\ n = 36,\ r = 0.773,\ p < 0.001 \qquad (10)$$

$$P = 53.404 + 0.282Z,\ n = 34,\ r = 0.5344,\ p < 0.001 \qquad (11)$$

The slopes of both (9) and (11) were significantly different from 0 (for (9): t = 4.003, df = 1, p <0.001; for (11): t = 3.257, df =1, $p < 0.01$) but for (10) it was not (t = 0.912, df = 1, p = 0.368). The relationship between Q and Z is shown in Figure 3. The estimated mean density of currently infested trees from fixed plots, prism plots, based on the parameters of equations (2) to (5) inserted into (6), and the parameters of (6) inserted into (8), and comparison of each mean with that from fixed plots, are given in Table 3. None of the mean comparisons in Table 3 was statistically significant.

Mean densities, variances and sample sizes for 50-m, 100-m, and 1000-m line transects, obtained by random sampling with replacement from the 36 line transects, are given in Table 4.

As the ratio (Standard Error/Density)^2 is approximately equal to c/n (Burnham *et al.* 1980), where n = the number of objects seen from the transect and c is a constant, this relation was used together with the data in Table 4 to estimate c. The estimated value of c tended to increase with line transect length and ranged from 2.036 to 3.701.

Table 3. Estimated mean density (ha^{-1}) of lodgepole pines currently infested by mountain pine beetle from fixed plots, prism plots and the parameters of equations (2) to (5) and (6) inserted into (7) and (8), respectively. Means were based on data from 36 line transects. Each mean was compared to the mean from fixed plots by paired t-test.

Estimate	Mean (SE)	Sample size (n)	t- statistic	Probability
Fixed plots	88.686 (12.192)	36	-	-
Prism plots	104.8476 (22.294)	36	1.277	0.206
Equation (2)	98.043 (14.957)	36	0.686	0.495
Equation (3)	97.910 (14.937)	36	0.677	0.500
Equation (4)	87.756 (13.388)	36	0.216	0.830
Equation (5)	75.268 (11.531)	36	-1.131	0.258
Equation (6)	83.183 (12.690)	36	0.434	0.674

Table 4. Mean density of currently infested lodgepole pine, variance, and sample size for each of three line transect lengths. Statistics for the 200 m and 1000 m long transects were generated by random sampling with replacement from field tallies of the number of infested trees seen from the thirty-six 50-m transects.

Statistic	50 m	200 m	1000 m
Density per hectare	87.757	79.597	83.154
Variance	6452.924	1617.990	525.646
Sample size	36	25	10

Discussion

Even though the average percentage per transect of trees misidentified by cruiser 2 (a person with limited experience in field identification of trees infested by mountain pine beetle) was about three times that of cruiser 1 (Table 1), the average density of confirmed currently infested trees found by the two cruisers was nearly identical (Table 3).

Cruiser 2 tended to make more errors of commission than did cruiser 1, especially at the higher densities of previously killed trees. The density of currently attacked trees and increased distance from the transect line both tended to increase the rate of errors of commission because (1) currently and previously infested trees were highly correlated (Table 2) and intermingled in the stands, and (2) it was increasingly more difficult to confirm the infestation status of trees with increasing distance from the line transects. On the other hand, the chance of such errors decreased with increasing average dbh and with the basal area and density of previously killed trees. In general, it was easier to positively identify currently attacked trees of larger diameter. As well, stand dbh was negatively correlated with both the density of currently attacked and previously attacked trees (Table 2) which tended to further reduce the chance of commission errors.

An important result with regard to the generality of the equations (4) to (6) was that the maximum distance from the line transect at which a confirmed currently infested tree was sighted was not related to any of the stand characteristics measured (Table 2). Only stand basal area had a significant effect on the average proportion of confirmed infested trees and that only for cruiser 1. However, this result indicates that stand basal area may affect the average probability of detection and the accuracy of predicted density based on (7) or (8) in some situations.

Since the line transects in this study were not established at random, but were often intentionally placed in areas containing the densest patches of currently infested trees, the shape of the detection curve (numbers seen vs. distance, Figure 2) declined in a curvilinear fashion. The probability of detection vs. distance relationship was, however, linear (Figure 1). In situations where the transect lines were distributed at random over the infested area, or systematically with a random start, the expected shape of the detection curve would be similar to the curve of the probability of detection (Figure 1).

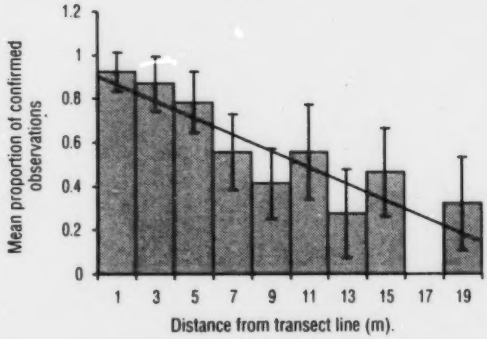

Figure 1. Frequency histogram of the mean proportion of confirmed currently infested lodgepole pine detected by two cruisers on 36 line transects (the bars indicate standard errors). The line represents the regression Yc = 0.9014 – 0.0356X (see equation 4 in the text).

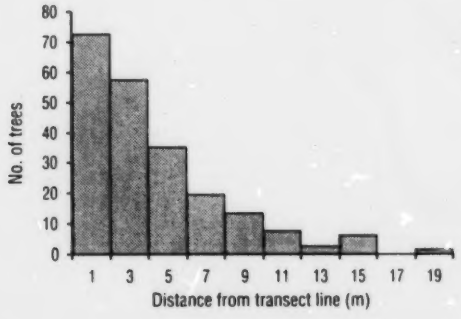

Figure 2. Histogram of the number of confirmed, currently infested lodgepole pines detected from 36 transect lines by two cruisers.

In fitting the linear regressions of the probability of detection on distance from the transect lines, we constructed a histogram by grouping data into nine 2-m distance classes. There appear to be no firm guidelines regarding the number of classes, as the number would depend partly on the number of observations and the shape of the detection curve. As a rule of thumb, 6 to 10 classes are considered appropriate for this type of data (Burnham *et al.* 1980). All data were pooled for construction of the histogram because there were inadequate numbers of observations on the individual transects.

The intercepts of regressions of the probability of detection on perpendicular distance from the transect line were significantly different from unity for (2) and (3). This indicates that the expected probability of detection of trees on the transect line (distance = 0) was less than 1. This occurred because the surveys were deliberately done at walking pace and some of the infested trees located on the line were overlooked. If all of the infested trees on the transect line had been found, it would most likely not have affected the slope of the lines. Consequently, the expected value of $\hat{u}$ in (1) would increase proportionately with an increase in the numbers of detected trees. Hence, density estimates based on (1) would not be substantially affected.

On average, the predicted density of currently attacked trees for individual transects (designated by Q) based on (4) and (7) closely tracked the corresponding observed density based on the fixed plot 100% survey (Z) (Figure 3). The relationship was linear (4), and variation of predicted density about the 45-degree line (where predicted density = observed density) increased approximately in proportion with observed density. This indicates that the coefficient of variation of the predicted values remained relatively constant throughout the range of observed values. Although the regression was linear and there was no significant difference in the overall mean density of currently infested trees between the estimates based on prism cruises (P) and line transects (Q), the intercept was significantly different from zero and slope significantly different from 1. On average, the estimated densities of currently infested trees based on the prism cruise were greater than those based on line transects. However, since the intercept and slope of the regression of P on Z behaved similarly, these results indicate that the prism cruise consistently overestimated the density of infested trees on the fixed plots.

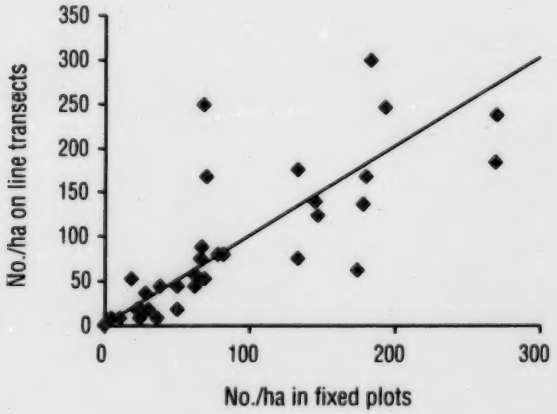

Figure 3. The relationship between lodgepole pine density currently infested by mountain pine beetle estimated from line transects (equations 4 and 7) and from complete survey of fixed plots centered on the transects (see Methods for details).

Detection functions (4) and (5) are nearly identical, indicating that the detection functions based on the average probability or the combined probability of detection for the two cruisers are the same. In practice, it is faster to do the cruises with two persons and estimates based on the combined counts would likely be more stable. For these reasons, it would be preferable if two persons carried out the surveys and density estimates from (7) were based on the slope and intercept of the combined detection function (4). The logistic function (6) also gave a good fit to the relation between the probability of detecting an infested tree and perpendicular sighting distance. Hence, (6) may be a detection funtion as reliable as those given by simple linear regressions. However, this model is more complex than the linear model and estimation of its parameters requires that the dependent variable be binomial (confirmed = 1, missed =0) and recorded for each infested tree together with the corresponding perpendicular distance. Grouping on sighting distance to calculate average probabilities, as was done for developing regressions (2) to (5), is not appropriate for (6). A quick description of developing estimates in small regions by line transect sampling is found in Melville and Welsh 2001.

The variance of the estimated density can be readily obtained in the usual manner if counts of sighted trees are based on independently located transects. If transect lines are of different length, density estimates should be weighted by transect length in calculating the sampling variance. In our study, the product of the squared coefficient of variation (CV^2) and the number of infested trees sighted (c) ranged from about 2.0 to 3.7. Evidence provided by Eberhardt (1978) indicates that the value of this variable c is quite stable and may typically range between 2 and 4. Based on the highest value of c (3.7), a desired CV^2 , and the number of sighted infested trees, n_1, obtained from a preliminary sample of length L_1, we can estimate the total length of the transect line, L, as follows:

$$L = (c/ CV^2)(L_1 / n_1).$$

In adapting this method of estimating infested tree density, a preliminary survey should be carried out to develop the cruiser's personal detection function(s), such as (2) to (6). Total length of the cruise lines for this work should be long enough that at least 200 infested trees are sighted. The number and length of cruise lines can vary as long as the target numbers of sighted infested trees were achieved. As much as possible, transect lines should be located at random within the area of infestation. Experience in identification of currently infested trees is highly desirable, as is a walking pace that accommodates sighting of all infested trees located on or near the transect lines. If no personal detection functions were developed, equations (4) and (7) could be used to generate rough estimates of infested tree density from counts of infested trees.

Though rigorous notes were not kept, a number of walk-throughs were timed; usually about 2-3 minutes were needed to complete a 50-m transect. In contrast, the time required to tally fixed or prism plots on the same lines was about 15 minutes, depending upon the number of trees requiring measurement.

We conclude that line transect sampling is an efficient method for estimating the density of lodgepole pines infested by mountain pine beetle. The field procedure requires only counts of infested trees and the distance traversed, which can be performed by one or two persons at a walking pace with considerable savings in time over establishment of fixed or prism plots. The counts can be readily incorporated into ground reconnaissance that is normally done each year to determine the spatial extent and intensity of infestations. The length of the transect lines needed to produce a predetermined degree of precision can be estimated.

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